Development of a Head and Eye Slaved Display System for a Rotary Wing Research Simulator

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SUMMARY

In order to meet the demanding visual requirements for flight simulation research on rotary wing combat, an approach was devised to control both display resolution and computer image level of detail based on eye point of regard in a fiber optic helmet mounted display. In support of that goal a helmet mounted eye tracking system was custom developed. This paper discusses the design requirements and performance considerations involved in the implementation of such a system.

Introduction

The Simulator Complexity Testbed (SCTB) is a highly modular device for experimental research on U.S. Army Aviation advanced rotary wing combat. The immediate goal of the SCTB program is to establish a flexible flight simulator research tool to address (1) aircrew training device fidelity requirements, (2) development and refinement of new aviation tactics and doctrine, and (3) front-end assessment of proposed operational capabilities in U. S. Army aircraft. The SCTB is intended to be operable within both local and long haul networked flight simulator environments (Ref 1), when so required for research purposes (Ref 2).

The SCTB system design incorporates a variety of innovative features, including: (1) microprocessor based distributed host computer system, (2) interactive tactical environmental management software tailored to the high intensity Army aviation battlefield, (3) upfront provisions to support the requirements for experimental research/data collection in advanced Army aviation combat, and (4) eye tracking to drive high detail computer generated imagery in an eye slaved AOI.

The principle SCTB display media is a fiber optic helmet mounted display (FOHMD). The FOHMD includes a moveable high resolution area-of-interest (AOI) as an integral part of the system design (Ref 3). The FOHMD visual image is formed from four computer image generator (CIG) channels, two channels per eye, one channel dedicated to a 24 degree by 18 degree high resolution inset, the

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14. ABSTRACT

To meet the demanding visual requirements for flight simulation research on rotary-wing combat, an approach was deviced to control both display resolution and computer image level of detail based on eye point of regard in a fiber optic helmet mounted display. In support of that goal, a helmet-mounted eye tracking system was custom developed. This paper discusses the design requirements and performance considerations involved in the implementation of such a system.

15. SUBJECT TERMS

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second channel used to produce an 82.5 degree by 66.7 degree lower resolution background field-of-view (FOV), respectively (Ref 4). This provides a total FOV of 127 by 66 degrees (Figure 1), with an overlap area of 38 degrees in which the imagery is stereoscopic (Ref 5).

Perhaps more than any of the defense related flight simulator applications, the image generation requirements for simulation of representative rotary wing combat environments severely push the state-of-the-art in flight simulator visual system technology (Refs 6 & 7). The solution provided by the SCTB to this requirement is to provide localized enhancement of both display resolution and CIG detail, continuously yoked to the observer's point of regard. The key to this approach is a helmet mounted eye tracking system. In addition to employing the eye position signal to drive wide excursion servo driven mirrors for moving the high resolution AOI, the point of regard data is coupled to the SCTB high fidelity image generator to control polygonal level-of-detail (LOD). In this system LOD falls off as a function of the angular horizontal distance from the center of the eye-slaved AOI, in addition to the normal polygonal LOD switching which occurs with increased distance from the eyepoint towards the horizon. Thus the highest level of CIG scene detail can be continuously concentrated in the area of highest display resolution. Different angular fall-off profiles may be pre-selected, depending on the requirements of a particular research experiment.

Figure 2 presents a block diagram of the major components which support the FOHMD/AOI system. They include an eye tracker, optical head tracker, servo controlled optical system, video blending electronics, and computational system.

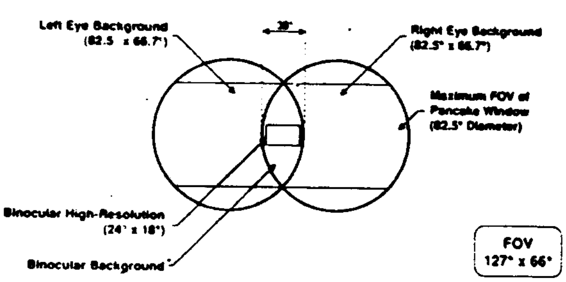


Figure 1. FOHMD Basic Fields of View

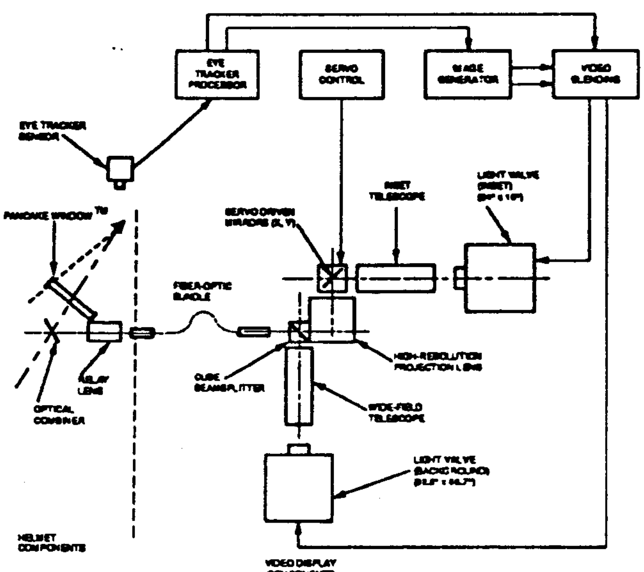


Figure 2. FOHMD/AOI Block Diagram

The development of a robust helmet mounted eye tracking system for this application was initiated under a cooperative U. S. Army/U. S. Air Force/Canadian Government cost shared development program.

Eye Tracker Design Considerations

Two characteristics of human vision provide the basis for an eye slaved AOI: (1) visual acuity is high within only a one degree area of the retina, called the fovea, and (2) visual acuity is reduced during and for a brief period following each saccade (Refs 8 & 9). Therefore, if a small area of high resolution imagery can be continuously maintained at the observer's fovea, by slewing that area along his point of regard (without exceeding his threshold for detection of displaced imagery), the observer's entire FOV will appear to consist of high resolution imagery.

To meet the requirements of this application, the eye tracker (ET) system must exhibit sufficient spatial and temporal resolution over the entire range of potential inset movement to assure that the point of regard remains continuously within the AOI. It must possess sufficient sensor sensitivity and signal processing sophistication to allow identification and rejection of artifacts in the eye position signal (blinks, spurious reflections, shadows, etc.). It must accommodate the expected velocities and accelerations of pilot eye movements (peak velocities in excess of 800 degrees/sec and accelerations of several thousand degrees/sec/sec.)

For use in a flight simulator environment, the ET must operate reliably and accurately under conditions of dynamically changing illumination caused by variations in scene brightness, which in turn can produce significant variations in the observer's pupil diameter. The impact of scene brightness is of special concern for the FOHMD, since the average luminance level of 30 Foot Lamberts (FL) is considerably higher than that obtained with typical flight simulator displays (nominally ten FL or less).

The ET must also perform without degradation over an acceptable range of expected variation in pertinent characteristics of the user population (in this case - Army aviators). These individual differences include pupillary response to light, corneal shape, iris color, and facial physiognomy.

Finally, the eye tracker must meet all of the above requirements under conditions of dynamic pilot head movement.

Eye Tracker Specifications

Table 1 lists the basic SCTB performance specifications established for the ET. Given the dimensions of the AOI (24 by 18 degrees) and the cumulative error over time that could result in a drift between the center of the AOI and the measured position of the eye, one degree of accuracy was selected as a design goal. The requirements for one-tenth of a degree resolution and 120 hertz (Hz) sampling rate were established to permit continuous repositioning of the AOI during smooth pursuit eye movements and for precision in measuring the onset/termination of saccades.

TABLE 1
Eye Tracker Specifications

Range:	+/- 30H/25V Degrees	Helmet Slip:	+/- 5 mm
Accuracy:	+/- 1 Degree	IR Illumination:	1mW/cm sqd
Resolution:	.1 Degree	Sampling Rate:	120 Hz

Ambient Luminance: 30 FL

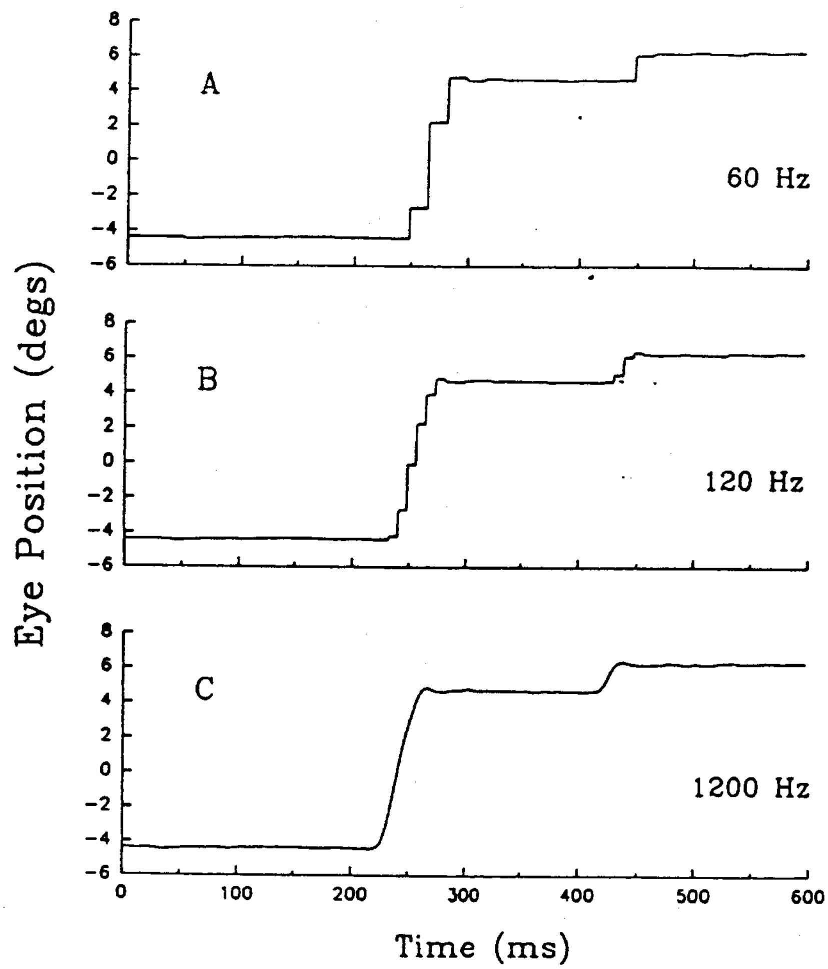


Figure 3. Effects of Sampling Rate on the Spatio-temporal characteristics of a saccade.

Multiple advantages accrue to high sampling rate. A higher iteration rate of measured eye position can significantly reduce the lag inherent in an AOI image, as well as reduce noise by providing a larger number of sampling points over which to average per unit time. Figure 3 shows the effects of three different sampling rates on the measured spatio-temporal characteristics of a saccade. By increasing the sampling rates from 60 to 120 to 1200 Hz, for example, the delays between the actual eye position and the data describing that position are reduced from 16.67 milliseconds (ms) to 8.33ms to .83 ms, respectively. With increasing sampling rate, the finer details of the saccade trajectory are increasingly discriminable.

In the present state-of-the-art, however, a tradeoff must be made between sampling rate and system resolution for real time application. Sufficient sensor data points must be sampled and processed in real time within each iteration to allow for accurate estimation of eye position. Improvements in available technology can be expected to significantly impact eye tracker capabilities in this arena in the near future.

Another feature essential for the present application is correction for translation artifacts, i.e., slippage of the helmet mounted ET relative to the head and eye. Given the head movements expected of pilots during combat simulation, some degree of head to helmet slippage is considered inevitable. The specifications for SCTB require that the ET system accommodate up to 5mm of helmet slip in all directions relative to the eye without degradation in tracking accuracy.

A study to determine a safe level of infrared (IR) illumination for the present application was specifically commissioned (Ref 10). That effort determined that an acceptable standard for IR illumination at the eye is 10mW/cm sqd. For the SCTB ET, however, a design goal of 1mW/cm sqd has been selected, which is less than 5 percent of the acceptable standard.

EYETRACKERS

Several ET system designs were developed specifically for evaluation on the FOHMD, each of which entailed enhancements to basic laboratory eye position measurement techniques (Ref 11), principally in the area of real time computational analysis. These systems differed in terms of signal processing algorithms, sensor array and choice of bright or dark pupil technique. Only two such ET designs will be discussed here.

For SCTB, eye position is determined by measuring the difference between the pupil centroid and a corneal reflection. This approach allows for a limited degree of translation of the ET relative to the eye before excessive error is introduced. As the eye rotates, the image of the corneal reflection moves relative to the image of center of the pupil, thereby providing the basis for determining eye movement magnitude. However, when the imaging system (sensor) slips relative to the eye, the images of the pupil and corneal reflection move at the same rate. Thus the difference measure is not contaminated by error due to sensor translation (within a limit of 5mm). Figure 4 shows the stability of this difference measure for a 5mm horizontal translation of the ET while fixating a stationary stimulus.

<u>Linear Array Bright Pupil ET</u>

An initially promising early prototype system developed for this program was based upon a bright pupil approach originally designed for medical research (Ref 12). It employed a single linear array of photodiodes, oriented either horizontally or vertically, as a function of desired axis of measurement. The SCTB prototype employed one such array per eye to permit measuring both axes, but a single combined system with perpendicularly oriented photodiodes for use on a single eye was also designed.

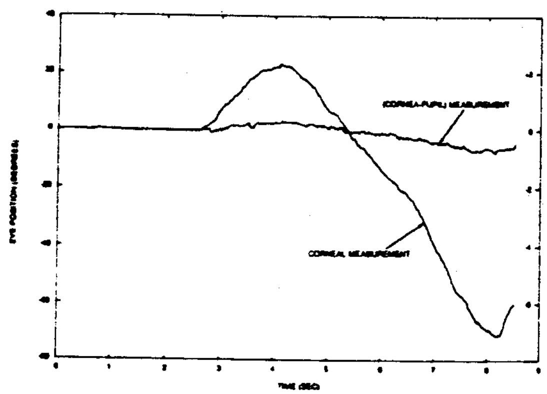


Figure 4. Effect of a 5mm Translation of the Eye Tracker

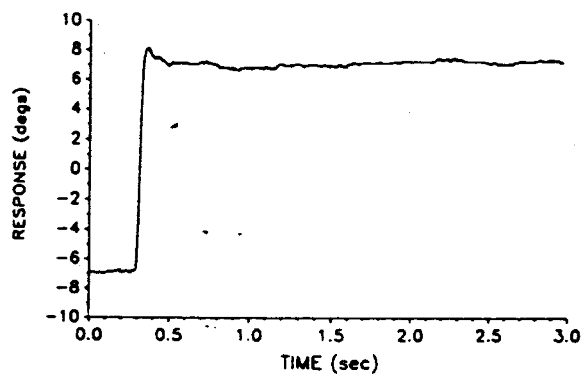


Figure 5. Linear Array Bright Pupil Step Response at 180 Hz

Figure 5 plots eye position sampled at 180 Hz as measured by this system on the FOHMD for a step change in target position from -7 to +7 degrees. Average noise was observed to be better that .2 degrees over a 15 degree range. Figure 6 plots 20 and 40 degree eye movements, respectively, as measured at 180 Hz.

Although this system was found to be capable of accurately measuring large amplitude eye excursions with remarkably low noise, unfortunately it could not maintain that level of performance reliably across a normal range of subjects. The ET failed for subjects whose pupil diameters were characteristically less than four millimeters under typical FOHMD luminance levels.

The bright pupil is produced by a retro-reflected image from the retina projected via the aperture formed by the pupil. Changes in pupil diameter caused by shifts in luminance cause variations in the intensity of the bright pupil signal. In addition, as the eye rotates away from the optical axis of the ET illumination source, the efficiency of the retro-reflection is degraded.

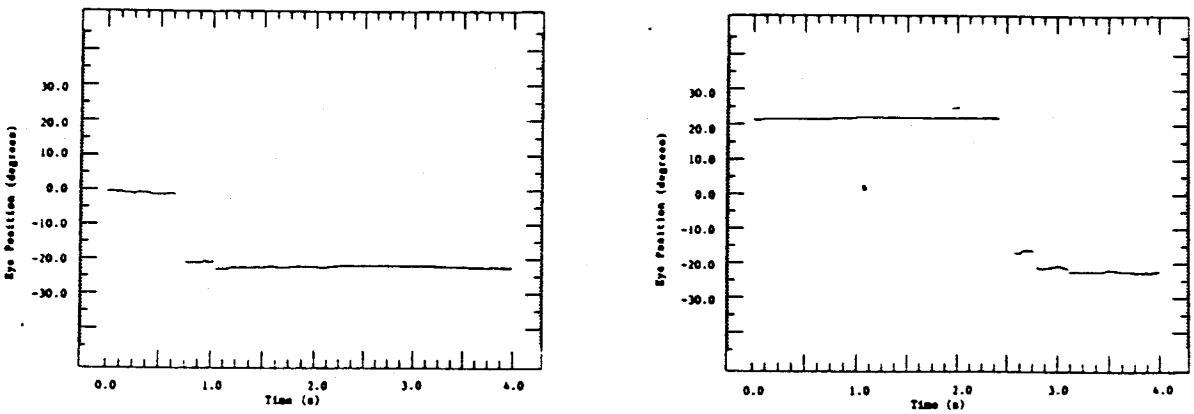


Figure 6. Linear Array Bright Pupil 180 Hz Data in Response to 20 degree (left) and 40 degree (right) Changes in Eye Position

Since these problems could be expected with any bright pupil system, particularly in view of FOHMD luminance levels, it was decided to modify the present approach to accommodate a dark pupil technique while retaining the power of the signal processing algorithms employed to estimate eye position.

TWO DIMENSIONAL CCD ARRAY ET

The image of the dark pupil formed by the pupil aperture acting as a light sink is far more robust than other methods, since the signal is not degraded by the effects of small pupil diameter and high luminance. However, shadows on the eye can serve as a significant source of error with this approach, so care must be taken to assure homogenous eye illumination.

The normal range over which a single corneal reflection may be reliably employed as an eye position referent is +/- 15 degrees, beyond which the signal often cannot be reliably discriminated from other aspects of the eye. One way to extend this range is to employ multiple corneal reflections, relying on the processing power of the computational system to select the best of several such candidate reflections for use in computing the pupil-corneal difference. For the present approach, the use of multiple IR

LED's for this purpose has the added advantage of enhancing homogeneity in eye illumination, thereby reducing signal noise and eliminating shadows.

In contrast to the linear arrays of photodiodes utilized in the previous prototype, the present ET employs a two dimensional Charge Coupled Device (CCD) array as a sensor system which is integrated into a custom fabricated camera for scanning the eye. Figure 7 presents a side view of the FOHMD and principle components, including the ET. Figure 8 gives an enlarged view of the ET system per se.

Figure 9 plots eye movement data collected on the FOHMD with this system while the observer tracked a smoothly moving CIG target along an elliptical path (+/- 15 degrees horizontal by +/- 10 degrees vertical) at an average velocity of 5 degrees per second. Correspondence between the target versus measured eye position was excellent.

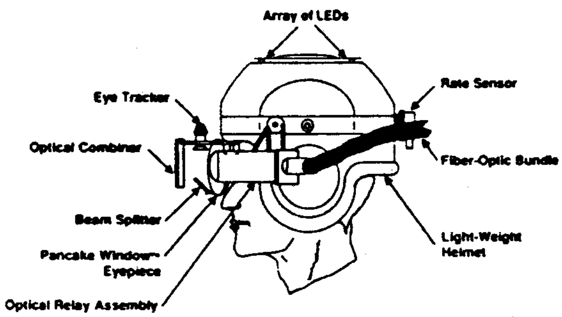


Figure 7. Side View of FOHMD

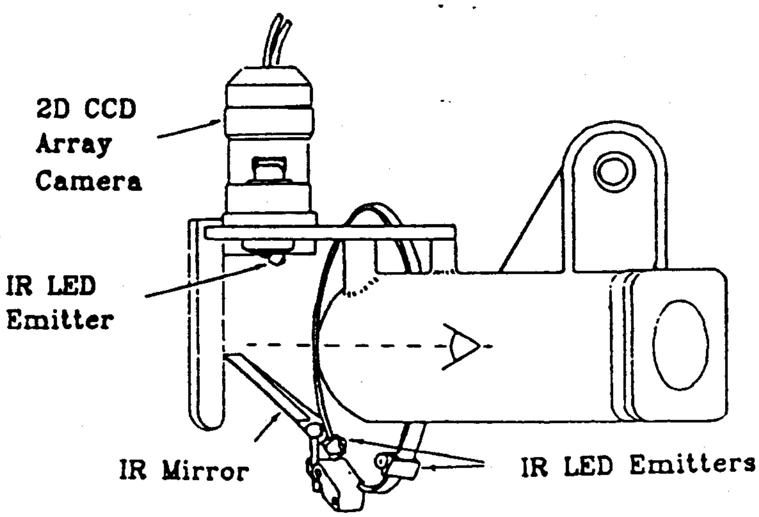
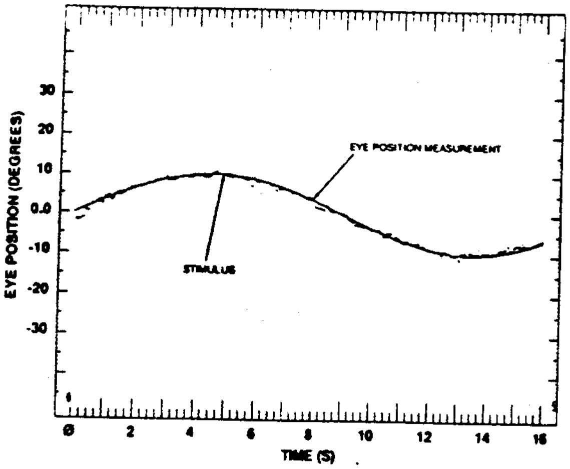


Figure 8. Mounting of Eye Tracker



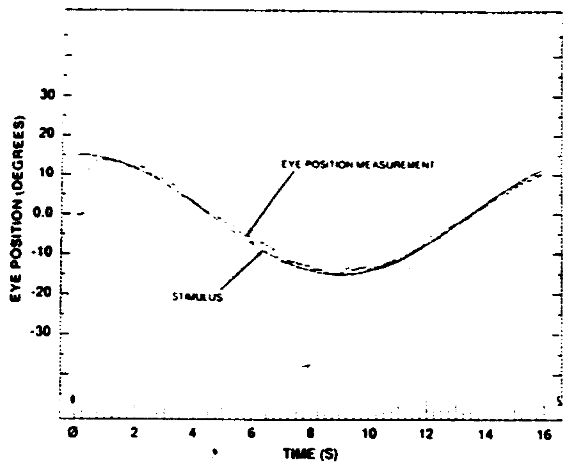


Figure 9. Dark Pupil CCD Array - Eye Position Data While Tracking a Smoothly Moving Target Along an Elliptical Path

A more rigorous test of the accuracy of the ET was also conducted in a controlled laboratory setting. For this study, subject movement was minimized by use of a dental bite bar, chin rest, and head support assembly to which the FOHMD optics with ET were also mounted. Prior to the start of the experiment, alignment of the left eye with respect to the exit pupil of the helmet optics was accomplished for each subject (N = 5) using an external light source. The ET was calibrated using a seven point procedure for horizontal and vertical axes, respectively, . The subject was seated a distance of 57 centimeters away from a 1.25H x 1V meter flat display screen on which a .1 degree diameter He-Ne laser spot target was rear projected. Target position was controlled by XY mirror galvanometer motors driven by a laboratory computer. Only one corneal reflection, taken from the nasal IR illuminator, was employed during this test.

Eye position measurements were taken along horizontal, vertical, and oblique axes, respectively. Thirty-one target positions corresponding to x and y coordinates of up to +/- 30 degrees in two degree increments from zero were employed, as appropriate for each such axis. Sequential target positions and durations were randomized, with data separately collected for each such axis. Only movements of the left eye were measured.

The results of this laboratory study are presented in Figure 10. Note that for each of the four axes presented, perfect ET performance would be represented by the straight line diagonal. For the horizontal axis, slight overestimation of eye position was observed at the temporal periphery; ET performance was otherwise excellent (except for an apparent anomaly at 12 degrees nasally, in which eye position was underestimated by nearly 6 degrees).

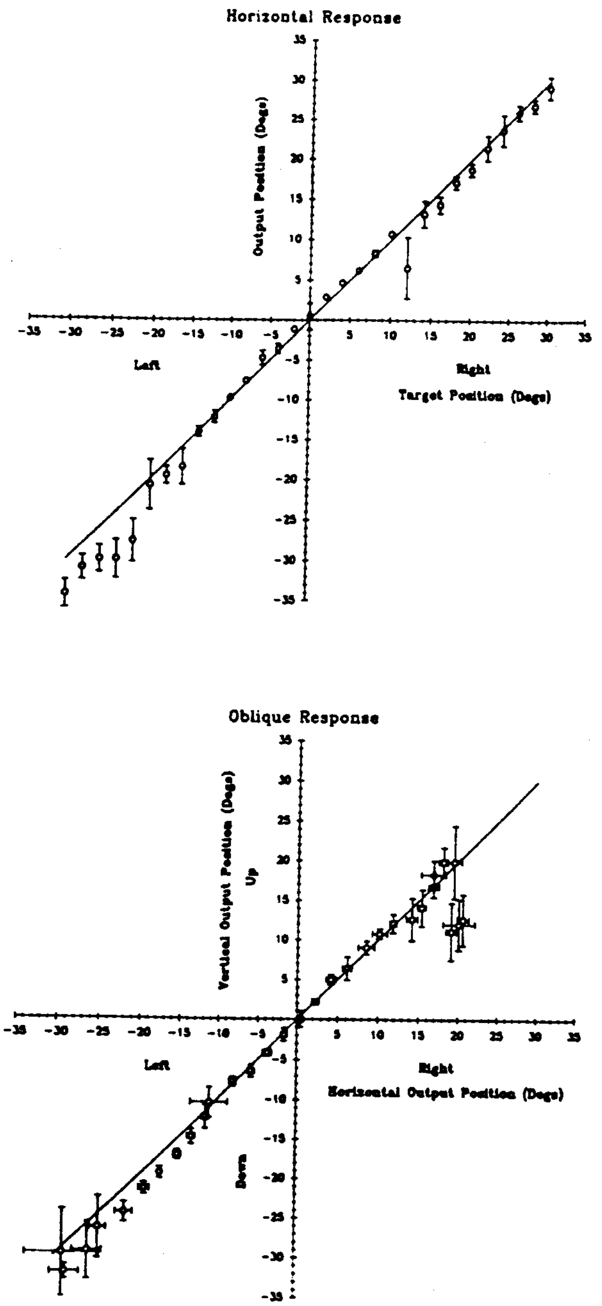


Figure 10. Dark Pupil CCD Eyetracker - Mean and Standard Deviation (N = 5) for Horizontal, Vertical, and Oblique Target Positions

ET performance along the vertical axis was also good, though offset error and variability were both observed to be greater for the upward target positions compared to down positions.

Lower left to upper right oblique results indicated slight overestimation of the vertical component for far temporal target positions. Nasal oblique accuracy was excellent until the far nasal periphery, where the FOHMD optical frames interfered with target visibility. Upper left to lower right oblique target positions produced a mirror image of these results.

In general, these data compare very favorably with published eye tracking results, particularly for target positions in the far periphery. These results are also encouraging with respect to accuracy achievable for AOI repositioning, especially since the ET tested is a prototype still in development, and further improvements in its configuration and processing power are expected. Laboratory data of this type are essential, however, in order to provide an empirical basis for any such product improvements.

Servo Design

In order to optically steer the AOI in elevation and azimuth within the lower resolution background, two servo driven mirrors rotating about orthogonal axes in the optics chain for each eye are employed. The output of the AOI image projector impinges first on the elevation axis mirror, which has a range of +/- 20 degrees (optically). Since the centerline of this mirror is not co-axial with the motor shaft, a high inertial load is encountered, which requires that a high torque DC motor be employed.

The image is then passed to the azimuth axis mirror, which is driven by a galvanometer motor. The azimuth servos have a range of +/- 50 degrees (optically). The resulting useful range of the AOI movement is approximately +/- 60 degrees horizontally by 25 degrees vertically.

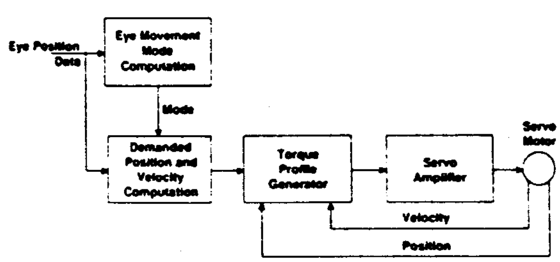


Figure 11. Eye Slaved AOI Servo Control

High speed digital processors control the servos based on position and velocity commands which are received from an eye position data processor. As indicated in Figure 11, this data is used to compute demanded motor torque profiles to move the mirror as required. Various modes of operation may be selected depending on the particular characteristics of the eye movement data (e.g. saccadic versus smooth pursuit response).

Video Blending

Video blending is employed to reduce the appearance of sharp boundaries at the intersection of the AOI and background. This system processes the video output of the CIG in real time to dynamically create a transitional region at the inset border. For this purpose the size of the blending region, the shape of the AOI, and other characteristics such as display gamma, may be preprogrammed. Experience to date suggests that a three degree blending region appears to be optimal. The circuitry then creates a cutout in the background, with a gradual transition region; it operates in a complementary manner on the inset video. The position of the cutout is determined by the eye tracking processor, and is timed so that synchronization between the CIG output, blending region position, and servo mirror position is maintained.

Optical Head Tracker

Since the display system is helmet mounted, the orientation of the visual scene and its dynamics must be appropriate to the observer's head position at all times. On the FOHMD the head position is sensed by a non-contact Optical Head Tracker (OHT).

The OHT (Ref 13) uses a ring of infrared LEDs mounted at the top of the helmet. These are sensed by four solid state optical position detectors, the output of which is transferred to the simulator host computer system for computation of head attitude and position.

In order to overcome throughput delays which would result in a lag in displayed imagery, rate sensors are also mounted to the helmet. A prediction algorithm combines the positional data from the LEDs with the rate data to supply a compensated head position to the CIG.

Eye tracking Processor

Raw data from the ET is transferred to the distributed microprocessor based host computer system for processing. Transfer rate is slaved to ET output rate, which can exceed that of the CIG (60 Hz) and other components of the simulator. The algorithms for determining required AOI position also run at the ET output rate. The output of the processing algorithms is combined with head position data as determined by the OHT to compute the viewpoint of each channel in the CIG.

Conclusions

Eye tracking technology was custom developed for the Simulator Complexity Testbed to drive both CIG scene detail and a high resolution AOI in a fiber optic helmet mounted display. Prototype evaluations conducted on the FOHMD as well as in a controlled laboratory setting indicate that acceptable eye tracker performance for this application can be achieved.

References

1. Thorpe, J. A., "Warfighting with SIMNET - A Report from the Front", In Proceedings of the 10th Interservice/Industry Training Systems Conference, National Security Industrial Association, Orlando, Florida, 1988.

2. Longridge, T. M., "An Approach to Airnet Program Evaluation", In Proceedings of the Symposium on Interactive Networked Simulation for Training, University of Central Florida, Orlando, Florida, 1989.

3. Hanson, C. L., Longridge, T. M., Welch, B., Kruk, R., & Barrette, R., "Fiber Optic Helmet Mounted Display, A Breakthrough in Full Visual Simulation", In Proceedings of the 1984 Society for Information Display International Symposium, Society for Information Display, San Francisco, California, 1984.

4. Kruk, R., & Longridge, T. M., "Psychophysical Research in the Development of a Fiber Optic Helmet Mounted Display", In Proceedings of the 20th Annual Conference on Manual Control, NASA Ames Research Center, California, 1984.

5. Kruk, R., & Longridge, T. M., "Binocular Overlap in a Fiber Optic Helmet Mounted Display", In Proceedings of the 1984 Image III Conference, Image Society, Phoenix, Arizona, 1984.

6. Bonzeit, F., & Edwards, R. E., "Image Generation for Rotary Wing Applications", In Proceedings of the 10th Interservice/Industry Training Systems Conference, National Security Industrial Association, Orlando, Florida, 1988.

7. Longridge, T. M., "Flight Simulator Training Effectiveness Research in U. S. Army Aviation", In Proceedings of the Royal Aeronautical Society Symposium on the Acquisition and Use of Flight Simulator Technology in Aviation Training, Vol. II, Royal Aeronautical Society, London, United Kingdom, 1987.

8. Stark, L, Kong, R., Schwartz, S, Hendry, D, & Bridgeman, B., "Saccadic Suppression of Image Displacement", Vision Research,

Vol. 16, 1976, pp 1185 - 1187.

9. Bridgeman, B., Hendry, D., & Stark, L., "Failure to Detect Displacement of the Visual World during Saccadic Eye Movements", Vision Research, Vol. 15, 1974, pp 719 - 722.

10. Frecker, R. C., "Ocular Hazards Associated with Exposure to Infrared Radiation", In R & D Status Report No. 84 for USAF Contract 70C3-81-R-0012, Wide-Field Helmet Mounted Infinity Display System, 1988.

11. Young, L, & Sheena, D., "Survey of Eye Movement Recording Methods", Behavioral Research Methods and Instrumentation, Vol. 7, 1975, pp 397 - 429.

12. Eizenman, M., Frecker, R. C., & Hallett, P. E., "Precise Non-Contacting Measurement of Eye Movements Using the Corneal Reflex", Vision Research, Vol. 24, 1984, pp 167 - 174.

13. Welch, B., & Shenker, M., "The Fiber Optic Helmet Mounted Display", In Proceedings of the 1984 Image III Conference, Image Society, Phoenix, Arizona, 1984.